“The Benefits of Nuclear Thermal Propulsion (NTP) in an Evolvable Mars Campaign”

presented by

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at the

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**NTR**: High thrust / high specific impulse (2 x LOX/LH₂ chemical) engine uses high power density fission reactor with enriched uranium fuel as thermal power source. Reactor heat is removed using H₂ propellant which is then exhausted to produce thrust. Conventional chemical engine LH₂ tanks, turbopumps, regenerative nozzles and radiation-cooled shirt extensions used -- “**NTR is next evolutionary step in high performance liquid rocket engines**”

During his famous Moon-landing speech in May 1961, President John F. Kennedy also called for accelerated development of the NTR saying this technology “gives promise of some day providing a means of even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself.”

NTP uses high temperature fuel, produces ~560 MWt (for ~25 klbf engine) but operates for ≤ 80 minutes on a round trip mission to Mars (DRA 5.0)
The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

- 20 NTR / reactors designed, built and tested at the Nevada Test Site – “All the requirements for a human mission to Mars were demonstrated”
- Engine sizes tested
  - 25, 50, 75 and 250 klbf,
- H$_2$ exit temperatures achieved
  - 2,350-2,550 K (in 25 klbf, Pewee)
- I$_{sp}$ capability
  - 825-850 sec (“hot bleed cycle” tested on NERVA-XE)
  - 850-875 sec (“expander cycle” chosen for NERVA flight engine)
- Burn duration
  - ~ 62 min (50 klbf, NRX-A6 - single burn)
  - ~ 2 hrs (50 klbf, NRX-XE: 27 restarts / accumulated burn time)

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* NERVA: Nuclear Engine for Rocket Vehicle Applications
Foundational Technology Development

System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis

- In-House & Contractor System Concept Definition, Design, and Analysis
  - Initial GTD Design
  - Initial FTD Design
  - Initial 25-klb GTD / FTD Designs
  - Reference Concept & Initial Requirements

NTP Technology Development and Demonstrations

- Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development
  - Primary / Secondary Fuels Selection
  - Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

NTP Test Facilities Development

- Borehole Demo Testing
  - Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests

Ground & Flight Technology Demonstrators

Ground Test Facility (GTF)

- Prel. & Final Design
- Construction & Asset Installation
- Check-out

Test Articles for Ground & Flight

- Detailed Design
- Fabrication & Subsys. Assembly
- Subsys. Test / Engine Assem.

Affordable SAFE Ground Testing at the Nevada Test Site (NTS)

NTR Element Environmental Simulator (NTREES)
Temperature Distribution Across FE and TT

Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)

FE + TT Cross Section And Path

ANSYS Model

Temperature Distribution Across FE and TT

Performance, Size & Mass estimation

MCNP neutronics for core criticality, detailed energy deposition, and control worth

Fuel Element-to-Tie Tube ratio varies with engine thrust level

Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

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MCNP neutronics for core criticality, detailed energy deposition, and control worth

Fuel Element-to-Tie Tube ratio varies with engine thrust level
"Heritage" Fuel Element Size Comparisons (Shown to Relative Scale)

- **ANL-200**
  - 61 Coolant Channels per element
  - 1.092 inch (2.774 cm)

- **GE-710**
  - 91 Coolant Channels per element
  - 0.928 inch (2.356 cm)

- **NERVA**
  - 19 Coolant Channels per element
  - 0.750 inch (1.905 cm)

• During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)

• NASA and DOE are using this same approach: design, build, ground then flight test a small engine using a common fuel element that is scalable to a larger 25 klbf thrust engine needed for human missions

**Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived NTR Engines**

**“Sparse” FE – TT Pattern used for Large Engines**

Each FE has 4 adjacent FEs and 2 adjacent TTs with a FE to TT ratio of ~3 to 1

**“SNRE” FE – TT Pattern used in Small Nuclear Rocket Engine**

Each FE has 3 adjacent FEs and 3 adjacent TTs with a FE to TT ratio of ~2 to 1

**“Dense” FE – Tie Tube Pattern used in Lower Thrust Engines**

Each FE has 2 adjacent FEs and 4 adjacent TTs with a FE to TT ratio of ~1 to 1

**NOTE:** An important feature common to both the Sparse and SNRE FE – TT patterns is that each tie tube is surrounded by and provides mechanical support for 6 fuel elements

### Performance Characteristics for Small & Full Size NERVA-derived Engine Designs – Composite Fuel

<table>
<thead>
<tr>
<th>Performance Characteristic</th>
<th>7,420-lbf Option</th>
<th>SNRE Baseline</th>
<th>Axial Growth Option</th>
<th>Radial Growth Option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal</td>
<td>Enhanced</td>
<td>Nominal</td>
<td>Enhanced</td>
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<tr>
<td><strong>Engine System</strong></td>
<td></td>
<td></td>
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<tr>
<td>Thrust (klb)</td>
<td>7.42</td>
<td>16.4</td>
<td>25.1</td>
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<td>Chamber Inlet Temperature (K)</td>
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<td>2695</td>
<td>2790</td>
<td>2940</td>
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<tr>
<td>Chamber Pressure (psia)</td>
<td>1000</td>
<td>450</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>Nozzle Expansion Ratio (NAR)</td>
<td>300:1</td>
<td>100:1</td>
<td>300:1</td>
<td>300:1</td>
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<tr>
<td>Specific Impulse (s)</td>
<td>894</td>
<td>875</td>
<td>906</td>
<td>941</td>
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<td>Engine Thrust-to-Weight</td>
<td>1.87</td>
<td>2.92</td>
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<td><strong>Reactor</strong></td>
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<td>Active Fuel Length (cm)</td>
<td>89.0</td>
<td>89.0</td>
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<td>Effective Core Radius (cm)</td>
<td>14.7</td>
<td>29.5</td>
<td>29.5</td>
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<tr>
<td>Engine Radius (cm)</td>
<td>43.9</td>
<td>49.3</td>
<td>49.3</td>
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<tr>
<td>Element Fuel/Tie Tube Pattern Type</td>
<td>Dense</td>
<td>SNRE</td>
<td>SNRE</td>
<td>SNRE</td>
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<tr>
<td>Number of Fuel Elements</td>
<td>260</td>
<td>564</td>
<td>564</td>
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<td>Number of Tie Tube Elements</td>
<td>251</td>
<td>241</td>
<td>241</td>
<td>241</td>
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<tr>
<td>Fuel Fissile Loading (g U per cm³)</td>
<td>0.60</td>
<td>0.60</td>
<td>0.25</td>
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<tr>
<td>Maximum Enrichment (wt% U-235)</td>
<td>93</td>
<td>93</td>
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<tr>
<td>Maximum Fuel Temperature (K)</td>
<td>2860</td>
<td>2860</td>
<td>2860</td>
<td>3010</td>
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<tr>
<td>Margin to Fuel Melt (K)</td>
<td>40</td>
<td>40</td>
<td>190</td>
<td>40</td>
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<tr>
<td>U-235 Mass (kg)</td>
<td>27.5</td>
<td>59.6</td>
<td>36.8</td>
<td>36.8</td>
</tr>
</tbody>
</table>

**NOTE:** Fuel Matrix Power Density: 3.437 MWt / liter

SOTA “Pewee-class” Engine Parameters


Glenn Research Center at Lewis Field
Small 7.5 klbf NTP Engine and Stage for 2025 Lunar Flyby FTD Mission

- IMLEO ~12.72 t
- F ~7.5 klbf, \( I_{sp} \) ~900 s,
- LH\(_2\) mass ~5.07 t
- Stage dry mass ~7.40 t
- Burn time ~20.9 mins

1. RL10 Fuel Turbopump
2. Core Length 35 (in) 88.9 (cm)
3. PV Dia. 35.9 (in) 91.2 (cm)
4. Regenerative and Radiation-cooled Nozzle
5. Exit Dia. 52.1 (in) 132.3 (cm)
6. Retractable Length 180.6 (in) 459 (cm)
7. Total Length 227.6 (in) 578 (cm)
8. LO2/LH2 RL10B-2 \( T_{vac} 24,750\text{-lbf} \)
9. Retracted Length 180.6 (in) 459 (cm)
"Heritage" Coated Particle & Composite SNRE FE / TT
Arrangement and Engine Performance Parameters

Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

(UC-ZrC) in Graphite “Composite” Matrix Fuel is NERVA Baseline

Table 2 - For Lunar Mission Applications

Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:
- Engine Cycle: Expander
- Thrust Level: 16.675 kblf
- Hydrogen Exhaust Temperature: 2726 K
- Chamber Pressure: 450 psia
- Nozzle Area Ratio: 300:1
- Specific Impulse ($I_{sp}$): ~900 s
- Hydrogen Flow Rate: ~8.4 kg/s
- F / $W_{eng}$ Ratio: ~3.06
- Engine Length: ~6.1 m
- Nozzle Exit Diameter: ~2.31 m
- FE Length ~0.89 m (~35 inches)
- FE-to-TT Ratio: ~2:1
- Reactor Power Level: ~367 MWt
- Fuel Matrix Power Density: ~3.44 MWt / liter
- U-235 Enrichment: 93%
- Fuel Loading: ~0.6 grams / cm$^3$
- U-235 Inventory: ~60 kg

(Ref: S.K. Borowski, et al., AIAA-2013-5465)
The NTPS with In-Line LH₂ Tank Allows Reusable Cargo Delivery and Crewed Missions to the Moon

Delivery of Habitat Lander to LLO (300 km)

Lunar Cargo Delivery:
- IMLEO ~186.7 t
- NTPS ~70 t
- In-Line LH₂ Tank ~52.6 t
- Habitat Lander ~61.1 t
- Burn time ~49.2 mins

NTP Lunar Cargo Transports Departing from LEO (407 km)

Crewed Lunar Landing:
- IMLEO ~188.6 t
- NTPS ~70 t
- LDAV and PL ~34.5 t
- MPCV, 4-Crew ~14.4 t
- Burn time ~55 mins
Crewed NTR NEA Survey Mission – Reusable Mode

NEA Rendezvous

Outbound Transit (A)

Trans-NEA Injection (TNI)

LH₂ Drop Tank Jettisoned

Crewed NTR Asteroid Survey Vehicle (ASV)

3 SLS / HLV Launches (~70 t – 140 t)

NEA Exploration (B)

MMSEV returns to the ASV

MMSEV detaches from ASV for close-up inspection / sample gathering sorties

Candidate NEAs (TNI): (A/B/C) days
- Apophis (5/8/28): (268/7/69)

After HEEO → LEO insertion, MPCV separates from ASV and re-enters

Initial ASV capture into a HEEO: 500 km x 71,136 km

Earth Entry

Velocity <12.5 km/sec

Crew recovery using MPCV

Direct Entry Water Landing

(Ref: S.K. Borowski, et al., AIAA-2012-5144)
“Searcher” and “Search Lite” ASV Options for Reusable and Expendable Missions to “Apophis” in 2028

(Ref: S.K. Borowski, et al., AIAA-2012-5144)

**Reusable Apophis Mission**
(LEO – NEA – 24-hr EEO)
- 6 Crew
- 3 – 25 klb NTRs
- 10 m dia. LH$_2$ tanks
- PL + MPCV ~62.3 t
- IMLEO ~326.2 t
- Max Lift ~138.1 t (NTPS)
- Total Mission Burn Time: 77.3 min

**Expendable Apophis Mission**
(LEO – NEA – Direct Entry)
- 4 crew
- 3 – 25 klb NTRs
- 8.4 m dia. LH$_2$ tanks
- PL + MPCV ~56.3 t
- IMLEO ~222.6 t
- Max Lift ~93.0 t (NTPS)
- Total Mission Burn Time: 43.8 min

(Ref: S.K. Borowski, et al., AIAA-2012-5144)
Reusable NTP Vehicles for NEA, Lunar Cargo and Crewed Landing Missions with Max Lift to LEO ~70 t

**Reusable NTP Vehicles**
- **Orion MPCV**
  - 4 crew
  - Max Lift ~70 t (NTPS)
  - Total Mission Burn Time: 54.5 min

**Lunar Cargo Delivery**
- (LEO – LLO – 24-hr EEO)
  - Habitat Lander ~61.1 t
  - IMLEO ~186.7 t
  - Max Lift ~70 t (NTPS)
  - Total Mission Burn Time: 49.2 min

**Crewed Lunar Landing**
- (LEO – LLO – 24-hr EEO)
  - 4 crew
  - LDAV + MPCV ~48.9 t
  - IMLEO ~188.6 t
  - Max Lift ~70 t (NTPS)
  - Total Mission Burn Time: 55 min

(Ref: S.K. Borowski, et al., AIAA-2013-5465)
Glenn Research Center

NTR Crewed & Cargo Mars Transfer Vehicles (MTVs) for DRA 5.0: “7-Launch” Strategy

3 – 25 klbf NDR Engines ($I_{sp} \sim 906$ s, $T/W_{\text{eng}} \sim 3.5$)

Common NTR “Core” Propulsion Stages

Saddle Truss / LH$_2$ Drop Tank Assembly

Payload Element $\sim 65$ t (6 crew mission)

“0-$g_E$” Crewed MTV:
- IMLEO $\sim 336.5$ t
- 3 HLV Launches

Cargo Lander MTV:
- IMLEO $\sim 236.2$ t
- 2 HLV Launches

Habitat Lander MTV:
- IMLEO $\sim 236.2$ t
- 2 HLV Launches

(Ref: S.K. Borowski, et al., AIAA-2009-5308)
NTR Crewed & Cargo Mars Transfer Vehicles (MTVs) for DRA 5.0: “7-Launch” Strategy

3 – 25 kib NDR Engines
($I_{sp}$ ~906 s, $T/W_{eng}$ ~3.5)

Common NTR “Core” Propulsion Stages

AC/EDL Aeroshell, Surface PL and Lander Mass ~103 t

Habitat Lander MTV:
- IMLEO ~236.2 t
- 2 HLV Launches

Cargo MTVs:
- Total Burn Time: ~38 min
- Longest Single Burn: ~22 min
- No. Restarts: 1

Cargo Lander MTV:
- IMLEO ~236.2 t
- 2 HLV Launches

3 – 25 kib NDR Engines
($I_{sp}$ ~906 s, $T/W_{eng}$ ~3.5)

Common NTR “Core” Propulsion Stages

AC/EDL Aeroshell, Surface PL and Lander Mass ~103 t

Habitat Lander MTV:
- IMLEO ~236.2 t
- 2 HLV Launches

(Ref: S.K. Borowski, et al., AIAA-2009-5308)
United States’ National Space Policy (June 28, 2010, pg. 11) specifies that NASA shall: By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars & return them safely to Earth.

**DRA 5.0 Crewed MTV Options:**

- **“4-Launch” in-line configuration**
  - Ares-V: 110 t; 9.1 m OD x 26.6 m L
  - IMLEO: ~356.5 t (6 crew)
  - Total Mission Burn Time: ~84.5 min
  - Largest Single Burn: ~30.7 min
  - No. Restarts: 3

- **“3-Launch” in-line configuration**
  - Ares-V: 140 t; 10 m OD x 30 m L
  - IMLEO: 336.5 t (6 crew)
  - Total Mission Burn Time: ~79.2 min
  - Largest Single Burn: ~44.6 min
  - No. Restarts: 3

Copernicus was sized to perform all fast conjunction missions in 2033-2045 period.
## Potential Evolution of Composite Fuel NTRE Size and Performance Levels Supporting the HAT “Evolvable Mars Campaign”

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Engine Thrust (klbf)</th>
<th>T/W_{avg}</th>
<th>T_{ex} (°K)</th>
<th>I_{sp} (s)</th>
<th>No. Engines</th>
<th>Fuel Loading (gU/cm³)</th>
<th>U-235 Mass (kg)</th>
<th>Longest Single burn (min)</th>
<th>Total burn duration (min)</th>
<th>No. burns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early FTD or Robotic Science</td>
<td>7.4</td>
<td>~1.9</td>
<td>2736</td>
<td>894</td>
<td>1</td>
<td>0.6</td>
<td>27.5</td>
<td>~20.9-22</td>
<td>~20.9-29.5</td>
<td>1-2</td>
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<tr>
<td>Lunar Cargo</td>
<td>16.7</td>
<td>~3.1</td>
<td>2726</td>
<td>900</td>
<td>3</td>
<td>0.6</td>
<td>60</td>
<td>~21.4</td>
<td>~49.2</td>
<td>5</td>
</tr>
<tr>
<td>Lunar Crewed</td>
<td>16.7</td>
<td>~3.1</td>
<td>2726</td>
<td>900</td>
<td>3</td>
<td>0.6</td>
<td>60</td>
<td>~20.9</td>
<td>~55</td>
<td>5</td>
</tr>
<tr>
<td>NEA - Apophis Piloted</td>
<td>25</td>
<td>~3.5</td>
<td>2790-2940</td>
<td>906-940</td>
<td>3</td>
<td>0.25</td>
<td>36.8</td>
<td>~25-37.2</td>
<td>~43.8-77.3</td>
<td>4-5</td>
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<tr>
<td>Mars Cargo</td>
<td>25</td>
<td>~3.5</td>
<td>2790-2940</td>
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<td>3</td>
<td>0.25</td>
<td>36.8</td>
<td>~22</td>
<td>~38</td>
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<tr>
<td>Mars Piloted</td>
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<td>~3.5</td>
<td>2790-2940</td>
<td>906-940</td>
<td>3</td>
<td>0.25</td>
<td>36.8</td>
<td>~44.5</td>
<td>~79.2</td>
<td>4</td>
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</tbody>
</table>

- The criticality-limited 7.4 klbf engine produces ~161 MWt of thermal power and has maximum fuel temperature of 2860 K.
- The 16.7 klbf SNRE produces ~367 MWt, and operates at a chamber pressure of ~3.1 MPa (~450 psia) with NAR ~300:1.
- The 25 klbf Pewee-class engine produces ~560 MWt of thermal power and has maximum fuel temperature of 3010 K.
- Other key performance parameters for the criticality-limited, SNRE & Pewee-class engines provided in NETS-2014 paper.

The engine design and mission performance parameters developed thus far provide important data to help guide future non-nuclear / nuclear irradiation testing and fuel down selection process.